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Evaluation of a Convective Scaling Parameterization for Estimating the Diffusion of a Buoyant Plume

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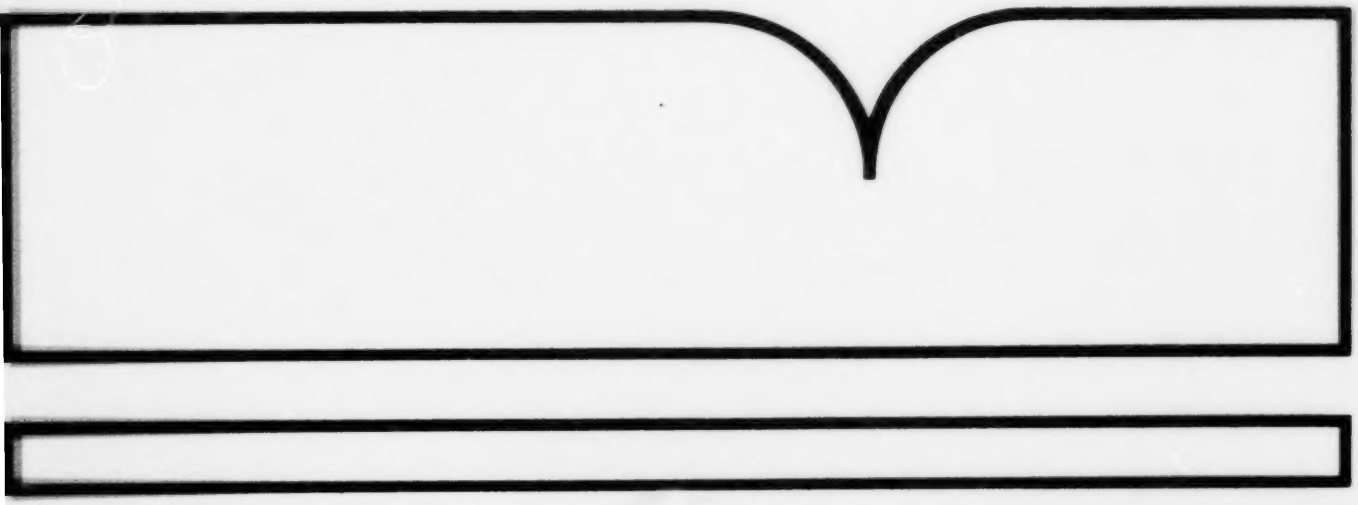

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AN EVALUATION OF A CONVECTIVE SCALING PARAMETERIZATION FOR ESTIMATING THE DIFFUSION OF A BUOYANT PLUME

by

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16. ABSTRACT

During limited-mixed convective conditions, high concentrations of air pollutants have been observed at ground-level from buoyant plumes. Routinely-applied Gaussian plume dispersion models have difficulty simulating diffusion for these conditions. However, advances in convective scaling offer some hope for improved model formulations.

This paper evaluates the usefulness of a diffusion formula proposed by Briggs. Thirty-nine hours of extensive meteorological, source, and tracer data were analyzed from the Kincaid field study. The evaluation of the Briggs formula compared to a Gaussian plume dispersion model showed better model performance.

Because of the sensitivity of the Briggs formula to values of w_* (convective scaling velocity), additional research is recommended to improve estimates of the sensible heat flux. Also, further study of the horizontal diffusion of buoyant plumes in the convective boundary layer is recommended.

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AN EVALUATION OF A CONVECTIVE SCALING PARAMETERIZATION FOR ESTIMATING THE DIFFUSION OF A BUOYANT PLUME

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INTRODUCTION

During limited-mixed convective conditions, high concentrations of air pollutants have been observed at ground-level from buoyant plumes. Gaussian plume dispersion models have been woefully inadequate in simulating diffusion during these conditions. However, beginning with towing tank studies by Willis and Deardorff (1974) and continuing with model development by Venkatram (1980) and Weil and Brower (1982), progress has been made using convective scaling parameterizations. Recently, Briggs (1985) introduced various diffusion parameterizations which included a formula for estimating the diffusion from buoyant plumes in the limited-mixed convective boundary layer.

This paper seeks to evaluate the usefulness of Briggs' formula by comparing it with observations made during the Kincaid field experiment (Bowne, 1981). Preliminary investigations by Pierce (1986) indicated that the Briggs parameterization offers an improvement to the Gaussian plume model. It is the purpose of this paper to test Briggs' formula with a more comprehensive data set from Kincaid and to examine some of the uncertainties in using the Briggs' formula.

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THEORY

Deardorff (1970) first noted that diffusion in the convective boundary layer could be scaled by two similarity parameters: the mixed-layer height, h, and the convective scaling velocity, w_*. The convective scaling velocity is defined by

$$w_* = \left[(g/\bar{T}_v)\ \overline{w'T'_v}\ h \right]^{1/3} \tag{1}$$

where g is the gravitational acceleration, $\bar{T}_v$ is the boundary-layer averaged virtual temperature, and $\overline{w'T'_v}$ is the kinematic surface heat flux.

Venkatram (1980) introduced a plume buoyancy parameter, F_*, for use in the convective boundary layer. It is defined as

$$F_* = F_b/(u\ w_*^2\ h) \tag{2}$$

where F_b is the buoyancy flux parameter and u is the boundary layer average wind speed.

Briggs (1985) suggested that the diffusion of buoyant plumes in the convective boundary layer could be scaled according to X/F_* which is equal to xw_*^3/F_b, where x is the downwind distance and X is the non-dimensional downwind distance (xw_*/uh). Using a limited amount of data from Weil (1977), Briggs determined an empirical fit for the non-dimensional cross-wind-integrated concentration C_y which is given by

$$C_y = \exp\left[-(7\ F_*/X)^{3/2} \right] \tag{3}$$

where C_y is defined by

$$C_y = h\ u \int \chi\ dy\ /\ Q \tag{4}$$

where $\int \chi\ dy$ is the cross-wind-integrated concentration and Q is the emission rate. Through dimensional arguments and an empirical fit of Weil's data, Briggs also suggested that the lateral dispersion of the buoyant plume, σ_y, could be determined from

$$\sigma_y = 1.6 F_*^{1/3}\ X^{2/3}\ h \tag{5}$$

By assuming that the lateral diffusion of the plume follows a Gaussian distribution ($\int \chi\, dy = \chi_c \sigma_y (2\pi)^{1/2}$), equation (3) and equation (5) can be used to obtain an expression for the centerline surface concentration, χ_c:

$$\chi_c = 0.250 \left[\exp-(7F_b/(xw_*^3))^{3/2}\right] / \left[F_b^{1/3} x^{2/3} h\right] \qquad (6)$$

Of particular interest in equation (6) is the sensitivity of χ_c to w_*. Later in the paper, we will examine how well the equation compares with observations and whether it offers an improvement to the commonly used Gaussian plume dispersion model.

DATA TO BE ANALYZED

The data used in the analysis were taken from the Kincaid field experiment described by Bowne (1981). Kincaid is a coal-fired power plant with one 187 m stack. The surrounding terrain is primarily flat to slightly rolling. Extensive measurements of meteorology, surface concentrations, and source conditions were taken during parts of 1980 and 1981. For this paper, we have analyzed conditions when the tracer gas SF_6 was released during convective conditions.

Meteorological measurements taken at Kincaid include hourly averages of wind speed, wind direction, temperature, and solar radiation collected on a 100 m tower. A Gill u,v,w anemometer located at the 100 m level yielded information on turbulence statistics. During intensive measurement periods, hourly balloon soundings provided vertical profiles of temperature and wind. Unfortunately, the balloon soundings did not include humidity measurements which would have given a better indication of the height of the mixed layer. Also, it was unfortunate that the meteorological tower did not contain a sonic anemometer for direct determination of the sensible heat flux. However, the data from Kincaid provide some of the most extensive diffusion measurements collected at an operational power plant of a buoyant plume.

During the intensive measurement periods, hourly concentrations of SF_6 were measured at 200 to 300 monitoring locations around the power plant. Typically, the monitoring network consisted of four to six arcs with monitors spaced about 2^0 apart. Arcs were situated at downwind distances ranging from 0.5 km to 50 km.

Source parameters which were available included hourly values for the SF_6 emission rate, stack gas exit velocity, and stack gas temperature. Typically, values for the buoyancy parameter, F_b, ranged from 600 to 2000 $m^4 s^{-3}$.

For the analysis, only those hours when the Briggs parameterization was applicable were selected. The following screening criteria were therefore used:

$$u/w_* < 6.0$$
$$0.09 < F_* < 1.0$$
$$p < 0.2$$

Values of $u/w_* < 6$ fall in the range of convective scaling suggested by Deardorff (1970), except that we also considered separately hours when u/w_* was less than 1.5. For the noted range of F_*, the buoyant plume is expected to "bump" against the elevated inversion, experience enhanced horizontal spreading, and gradually diffuse downward by convective eddies. According to Briggs (1985), when $F_* < 0.09$, the buoyant plume is not expected to interact significantly with the elevated inversion. When $F_* > 1$, significant plume penetration into the elevated inversion is expected. A quantitative measure of plume penetration was determined by p, the fraction of plume mass estimated to penetrate into the elevated inversion. Briggs (1984) defined p as

$$p = \left[3.9 - (h - h_s)/(F_b/us)^{1/3} \right]/2.6 \qquad (7)$$

where h_s is the stack height (187 m) and s is the stability parameter in the elevated trapping inversion ($g/\theta\ \partial\theta/\partial z$).

In addition, hours with excessive wind shear, precipitation, and when the plume was not fully captured by the sampling arc were not analyzed. The data used in the analysis are summarized in Table 1.

Table 1. Summary of meteorological, source, and receptor data from the Kincaid field experiment.

Date	Hr	u (m/s)	PG class	z_i (m)	F_b ($m^4 s^{-3}$)	w_* (m/s)	F_*	Q (kg/hr)	Approximate arc distances (km)
7/10/80	14	5.0	C	900	1848	1.0	0.41	46.7	7,14
7/13/80	14	2.0	B	500	566	1.3	0.33	47.6	4,6,7,10
	15	1.7	B	550	563	1.2	0.42	47.6	4,6,7,11
	16	1.6	B	600	563	1.1	0.48	48.5	3,7,11
7/14/80	12	5.8	B	500	1700	1.3	0.35	44.0	0.5,2,3,7
	13	5.2	B	600	1694	1.2	0.38	48.1	1,3,14
7/23/80	10	2.7	B	825	1189	1.6	0.21	47.6	1,2,6,7
7/24/80	11	2.8	A	1600	2210	1.9	0.14	46.3	3,5,16,20
	12	2.7	A	1600	2243	1.9	0.14	47.2	1,4,5,16,21
	13	2.8	A	1600	2274	1.8	0.16	47.6	1,3,5,16,21
	14	2.3	B	1700	2275	2.1	0.13	48.5	1,3,5,15,21
	15	1.9	B	1800	2406	1.7	0.24	49.4	1,3,5,8,21
	16	1.9	B	1700	2336	1.3	0.43	49.9	3,5,8,21
7/28/80	13	2.8	A	1400	1298	1.6	0.13	44.9	2,3,5,13,20
	14	2.3	B	1400	1299	1.5	0.18	72.6	5,7,14
	15	2.2	B	1400	1308	1.7	0.15	43.5	1,2,3,5,7,14,20
	16	2.9	B	1200	1425	1.4	0.21	61.2	5,14
	17	2.9	C	1300	1577	1.0	0.42	43.5	3,20
7/29/80	10	4.2	B	550	1523	1.4	0.34	44.0	2,14
	11	3.8	B	600	1597	1.7	0.24	51.7	2,6,14
	12	4.5	B	600	1713	1.7	0.22	62.6	2,3,5,6,14
5/15/81	10	6.8	C	450	1123	1.3	0.22	57.2	3,5,10,19,47
	11	4.9	B	550	1154	1.3	0.25	54.4	3,5,10,19,28,49
	12	4.4	B	550	955	1.2	0.27	57.6	20,31
5/27/81	11	1.6	A	800	1037	1.2	0.56	41.7	2,4,6,7
	12	2.1	A	1000	1017	1.4	0.25	42.2	2,4,6,7,9
	13	2.6	B	1350	1047	1.6	0.12	44.9	2,5,6,7
	14	2.9	B	1200	1027	1.6	0.12	44.9	5,7
	15	2.7	B	1600	903	1.5	0.09	44.9	5,6,7
	16	3.6	C	1400	923	1.2	0.13	44.9	2,5,6,7
	17	3.2	D	1300	943	0.7	0.46	44.9	2,5,7
5/28/81	11	2.7	A	925	983	1.4	0.20	44.0	0.5,1,3,5,7,14
	12	2.6	A	1200	1023	1.3	0.19	46.7	1,2,3,5,7,14
	13	3.2	A	1300	1000	1.4	0.12	47.6	0.5,1,2,3,7,14
	14	3.4	B	1300	1025	1.4	0.12	45.8	0.5,1,2,3,7,14
	15	3.2	B	1400	1024	1.3	0.14	43.5	0.5,1,2,3,7,14
	16	3.4	B	1600	992	1.3	0.11	44.0	1
	17	3.8	C	1500	961	1.0	0.17	44.9	0.5,1,2,3
5/29/81	11	7.7	C	650	1026	1.4	0.10	42.2	1,2,4,7,14

ANALYSIS OF THE DATA

Several steps were needed to obtain the data necessary for comparison to the Briggs equation. These included estimating the boundary-layer height (h), estimating the convective scaling velocity (w_*), and computing the cross-wind-integrated concentration. Once these parameters were determined, observations were compared to predictions for values of the normalized cross-wind-integrated concentration (C_y) and centerline concentration (χ_c).

Boundary-layer height

The method chosen for determining the boundary-layer height uses hourly temperature soundings. The height of a significant increase in potential temperature was assumed to be the top of the boundary layer. Some temporal smoothing of the hourly mixing heights was employed to maintain continuity between soundings.

Convective scaling velocity

Estimates of w_* were perhaps the most uncertain aspect of this study. Yet, concentration estimates using Briggs' parameterization are extremely sensitive to w_* which is dependent on an estimate of the sensible heat flux. Because direct measurements of the sensible heat flux were not available, we had to rely on indirect methods. Approaches that were considered included those of Holtslag and van Ulden (1983) and Irwin and Binkowski (1981). We also considered using the difference in hourly temperature profiles to obtain the hourly sensible heat flux. However, estimates of the sensible heat flux were found to be sensitive to small differences in the vertical temperature profiles which contained uncertainties due to calibration offsets and horizontal temperature advection. Therefore, the hourly soundings were not used for determining the sensible heat flux.

The two methods which were considered, Holtslag/van Ulden (HvU) and Irwin/Binkowski (IB), use routine meteorological data. With the HvU method, measurements of net radiation were used in parameterizing the sensible heat flux. With the IB method, measurements of the 2-10 m temperature difference and the 10 m wind speed were used to determine a

bulk Richardson number. Values of w_* using the two methods are compared in Figure 1 for the 39 hours of data that were analyzed. Figure 1 shows that the HvU method results in w_* values that are more than 20 percent (0.4 m/s) higher than with the IB method. Because the HvU method relies on several empirical constants which have not been fully tested for the continental climate of the United States (Wilczak and Phillips, 1986), it was decided to rely on the IB method for this study.

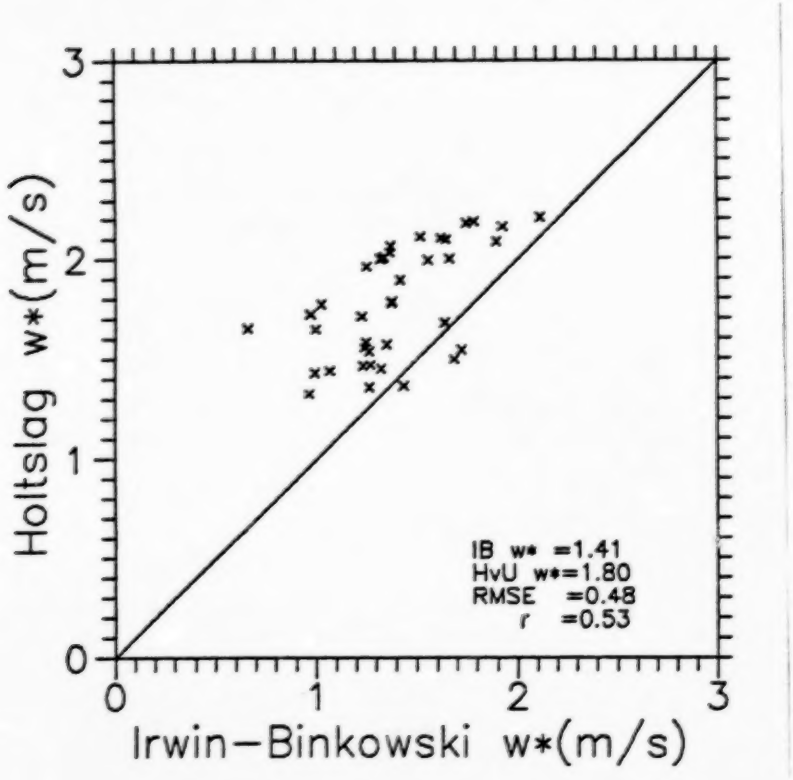

Figure 1. Comparison of computed w_* values.

Cross-wind-integrated concentration

Unfortunately, no definitive reference exists on how to compute cross-wind-integrated concentrations from actual monitored data. For this analysis, the following approach was used:

(1) For all non-zero concentrations along an arc, a concentration weighted radial distance was determined from

$$\bar{r} = \left[\sum_{i=1}^{n} \chi_i r_i \right] / \left[\sum_{i=1}^{n} \chi_i \right] \qquad (8)$$

where χ_i is the concentration at each receptor, i, and r_i is the radial distance to each receptor.

(2) The cross-wind-integrated concentration was determined by

$$\int \chi \, dy \cong \bar{r} \sum_{i=1}^{n-1} \left[\left(\chi_i + \chi_{i+1} \right) / 2 \right] \left[| \alpha_i - \alpha_{i+1} | \right] \qquad (9)$$

where α_i is the azimuth of receptor i relative to the source. To properly determine $\int \chi \, dy$, the concentrations at receptors 1 and n had to be zero.

In computing values for the cross-wind-integrated concentration, arcs were excluded from the analysis if there was excessive variation in the radial distances or if it appeared that the width of the plume was not included on the sampling arc.

Examination of C_y

From the observed values of the cross-wind-integrated concentration, values for C_y were computed using equation (4). A total of 166 values were determined from the Kincaid data. Values for C_y plotted relative to X/F_* are shown in Figure 2. The circles represent observations made when u/w_* was less than 1.5, and the "x"s represent observations made when u/w_* was greater than 1.5. The solid line in Figure 2 depicts the theoretical curve of Briggs (equation 3).

The data from Kincaid show reasonably good agreement to the Briggs curve. Scatter in the C_y values is more pronounced at small X/F_* values, but beyond $X/F_* = 10$, over 70 percent of the observed C_y values are within a factor of two to the Briggs curve. C_y values associated with low u/w_* conditions tend to be lower than the curve, but they follow the same trend as the C_y values associated with higher u/w_* conditions. One may be tempted to fit a better curve to the observations, and an equation in the form of $\exp[-10F_*/X]$ does indeed produce a slightly better fit. However, considering the scatter in the data, the Briggs curve appears to be adequate.

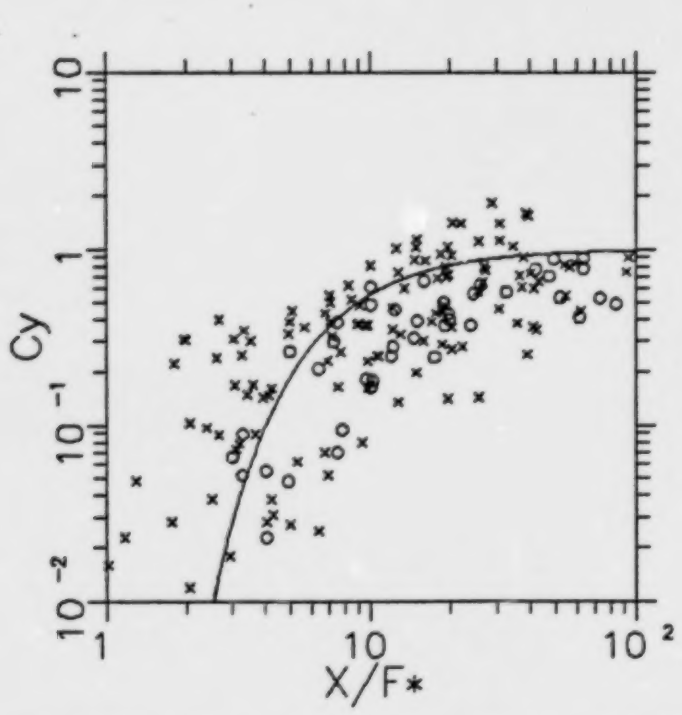

Figure 2. Comparison of Kincaid C_y values to the Briggs curve.

Centerline Concentrations

The next step in the analysis is to compare estimates of centerline concentrations to observations. From each arc, the highest monitored concentration was assumed to represent the centerline concentration. Centerline concentrations were then estimated with equation (6) and a Gaussian plume model, MPTER (Pierce and Turner, 1982). Estimated centerline concentrations are compared with observations in Figure 3.

Figure 3 shows the superiority of the Briggs equation compared to the Gaussian plume model. Nearly 55 percent of the Briggs estimates are within a factor of two of the observations, but less than 25 percent of the Gaussian model estimates are within a factor of two. Also, the Gaussian plume model predicted zero ground-level impact for more than 50 percent of the cases. This is caused by the failure of the Gaussian model to consider plume "bumping". It instead assumes that the plume either lofts above the mixed layer or is fully contained within the mixed layer, depending on the plume rise estimate. Despite its good performance, the Briggs equation tends to underestimate the observed concentrations by an average of 30 percent. This underestimate could be caused by the σ_y formulation (equation 5). In fact, reducing the constant in equation (5)

from 1.6 to 1.1 would increase estimates of centerline concentrations by about 30 percent. However, modifications to the σ_y formulation deserve further comparison to field data.

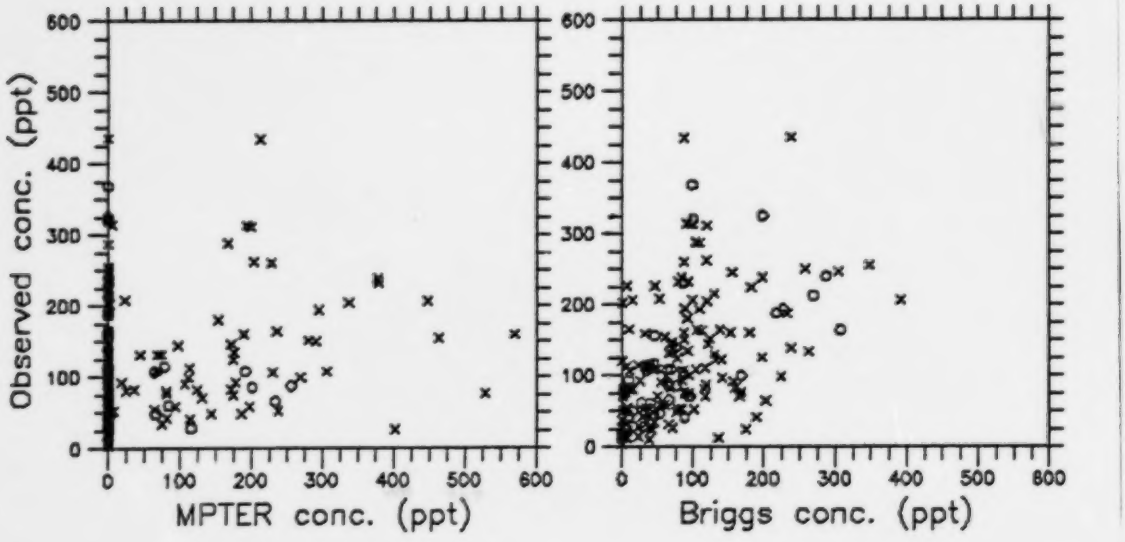

Figure 3. Comparison of observed centerline concentrations to estimates from the Briggs parameterization and a Gaussian plume model (MPTER).

SUMMARY

The convective scaling parameterization suggested by Briggs (1985) for estimating diffusion in a convective, limited-mixed boundary layer has been tested with data from the Kincaid field experiment. The results show improved estimates compared to a Gaussian plume dispersion model.

Because of the sensitivity of the Briggs parameterization to w_*, additional work is needed to improve sensible heat flux estimates and to minimize observational errors from upper-air soundings which affect mixing-height estimates. While the observed concentrations indicate that the Briggs parameterization performs reasonably well for low u/w_* values, the possiblity of upstream diffusion as suggested by Deardorff (1984) needs to be explored. Also, further study of the horizontal diffusion of buoyant plumes in the convective boundary layer is recommended.

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